THE ROLE OF BINARY MIXTURES OF PARTICLES ON AIR-SIDE FOULING OF COMPACT HEAT EXCHANGERS

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Abstract

Air-side fouling of compact heat exchangers (automobile radiators) has been a preoccupation for industrial users of off-road vehicles for many years. Until recently, most studies examined the effects of small sized particles in the 1–100µm diameter range. The present work concentrates on fouling of the inter-fin space (IFS) by binary mixes of larger particles (up to some mm in length). Each mix comprises 95% by weight of "smaller" particles and 5% "larger" particles. The threshold size is the critical value of 0.63 times the maximum IFS. Two exchangers (A & B) are studied experimentally with maximum IFS(A) being 3mm with particle sizes up to 4mm in length and exchanger B having corresponding values of 1.38mm and 1.6mm respectively.

Pressure drop and the proportion and dispersion of particles that contribute to fouling are measured as a function of air speed (up to 5m/s or 18km/h, typical of off-road vehicles) and particle size mix for isothermal and non-isothermal conditions. These are complemented by visualisation.

The results show that the foulant is not simply the cumulative effect of both particle sizes. There is a distinct interaction between them leading to a greater number of particles being blocked on the exchanger. The physics behind this are discussed in detail. The importance of the critical size particles in the augmentation of fouling is clearly demonstrated and explained.

It is possible to define an equivalent particle size for any binary mixture by comparison with the pressure drops for mono-disperse particle sizes leading to a unique curve for the fouling factor reduced by exchanger surface and particle mass as a function of non-dimensional particle size.

Heat transfer measurements (with water temperature at 60°C or 70°C at exchanger entry) in a wind tunnel with closed and open sides show the dangers of the former leading to erroneous conclusions.

Introduction

Haghighi-Khoskhoo & McCluskey 2007 previously examined heat exchanger fouling by mm-size particles with specific emphasis on the size likely to be the most detrimental to performance for a given exchanger. Those experiments involved placing an exchanger in a wind tunnel and seeding the airflow with particles of one size for a given run. The individual particle sizes ranged from those that can enter and pass through the exchanger without being hindered (determined experimentally) up to the largest that may physically enter the inter-fin spacing. For the exchangers examined here, this maximum is up to 4mm. This entire set was broken up into 5 or 6 sub-ranges (see Table 1) which were then studied individually. Small particles, below 0.2mm, are not within the scope of the present work.

Table 1 Particle range sizes (mm) for exchangers

Range	Exchanger A	Exchanger B
A1 / B1	0.20 < d < 0.80	0.20 < d < 0.25
A2 / B2	0.80 < d < 1.25	0.25 < d < 0.50
A3 / B3	1.25 < d < 1.85	0.50 < d < 0.80
A4 / B4	1.85 < d< 2.00	0.80 < d < 1.25
A5 / B5	2.00 < d < 3.15	1.25 < d < 1.60
A6 / --	3.15 < d < 4	

Experiments showed that there was a specific critical size for which the fouling was most ingrained, i.e. which were most detrimental to thermal performance as they block the airflow through it. The majority of these critical size particles entered into the inter-fin space (which we refer to as sub-surface fouling) and lodged in a zone of depth of a few mm behind the front surface. Notably, they were very difficult to remove during later cleaning. Smaller particles (below critical size) generally passed through the exchanger while the larger sizes had a greater tendency to block at (or bounce off) the front surface, falling to the ground when the air flow was switched off.

A brief non-dimensional geometrical analysis helped predict this critical size range for any finned exchanger. It is 0.63 times the diameter of the largest sphere that can be inscribed between the fins. Confirmation of this was found with a second exchanger. The addition of humid

ISBN: 978-0-9984188-0-3; Published online www.heatexchanger-fouling.com

conditions within the tunnel or on the exchanger itself did not modify these values.
Pressure drop measurements across both clean and fouled exchangers confirmed that the foulant acted like an extra mechanical filter in series with the exchanger. This is quite understandable given the short penetration length of the particles (up to 3 mm).

However, this previous work involved only single discrete size ranges of particle.
A more complete study of air side fouling must include a systematic treatment of fouling by different size ranges interacting together. Here, the poly-disperse nature of fouling is approximated by combining distinct particle size ranges in binary mixtures in typical proportions.

In 1981 Cowell & Cross analysed the foulant on a number of exchangers taken from road vehicles and noted that large size particles found in the foulant accounted for 7% by mass of the total, most of which did not penetrate into the exchanger core. These millimetre sized particles were made up of dust, oil droplets, fibrous matter, insects etc.
Clearly, discrete size ranges are somewhat idealistic when compared to real fouling so we base our study on the effects of larger particles that effect the macro-scale performance, in particular the works of Cowell & Cross 1981, Bott & Bemrose 1983, Bott 1995, Lankinen et al 2000a & 2000b and Siegel & Carey 2001 and Siegel & Walker 2001.

Cowell & Cross followed up their observations with wind tunnel measurements on a further 22 exchangers which involved oil droplets included with the particles. Without the oil they noted that the smallest particles (up to 40µm) passed through the exchangers unhindered whereas there was significant fouling with the oil. The oil and particles barely penetrated into the exchanger core, remaining close to the outer surface, but they measured a significantly higher pressure drop across the exchanger as a result of the fouling. An important (and unfortunately erroneous) conclusion of their wind tunnel measurements was that the fouling had little or no effect on the heat transfer. This specific point will be returned to later. Surprisingly they did not look at the effects of a small proportion of larger particles. They defined the fouling coefficient and correctly showed that the foulant acted like an extra filter screen placed in front of the exchanger, the overall pressure drop being the addition of that for the foulant added to that of the clean exchanger.

Bott et al 1983, 1995, carried out their experiments in a vertical wind tunnel using calcium carbonate particles (up to 30µm in diameter) and an adhering agent to help them stick. They measured a friction factor law with Reynolds number that did not depend on the state of fouling on the exchanger and concluded as Cowell & Cross 1981 that the foulant acted as a supplementary filter in front of the exchanger.

Lankinen et al 2000a, 2000b performed their experiments in a wind tunnel and measured pressure drop and heat exchange during fouling. They included a small proportion of larger particles in their impacting flow. Their results showed that the pressure drop increased by up to 400% when the larger particles were present compared to the single size particle experiments. They also measured a decrease in heat exchange performance of up to 18% following significant fouling, a phenomenon not found by other researchers using wind tunnels. However, they simply mentioned this without giving any detail or explanation. As with the other authors they found low foulant penetration into the exchanger with similar conclusions.

Siegel & Carey 2001 and Siegel & Walker 2001 examined the fouling of coil type exchangers and noted the strong effect of a small amount of larger particles on the fouling coefficient. They did not expand on this beyond the observation.

For this reason it was decided to study the fouling of exchangers by binary mixtures of particles which comprise 95% by mass of “smaller” particles, i.e. smaller than the critical size that can generally pass through the exchanger without precipitating, complemented by 5% of larger size (critical size and above). All particles are capable of entering into the inter-fin spacing to a greater or lesser extent.

Experimental techniques

The reader is referred to Haghigi-Khoshkoo & McCluskey 2007 where the actual experiment and measurement techniques are described. Two exchangers were studied with the characteristics shown on Table 1. Exchanger A is an older model with low density fin spacing whereas exchanger B is used by Peugot in their 206 model. Fin geometry in both is trapezoidal.

The exchangers could be placed in the closed test section of an open circuit, 40 cm x 40-cm, wind tunnel equipped with pressure and temperature sensors. Air velocity was measured and continuously controlled to ensure that the pressure drop across the exchanger did not alter experimental conditions. The pressure tappings were on the wind tunnel side wall some cm upstream and downstream of the exchanger. Wind velocities did not go beyond 5 m/s.

The water passing through the exchanger was heated via a thermostated bath and thermocouples were situated at exchanger entry and exit. Maximum flow rates were 180 l/h for exchanger A and 140 l/h for B. Entry temperatures were set at either 60°C or 70°C. Waterside tube diameter was 6mm.

Table 2: Relevant exchanger characteristics

Exchanger	A	B
Fin density/100mm	44	95
Fin spacing at base	3.00 mm	1.38 mm
Fin spacing at summit	1.60 mm	0.64 mm
Fin length	18.5 mm	7.60 mm
Fin thickness	0.15 mm	0.10 mm
Exchanger depth	30 mm	28 mm

Particles were introduced into the flow through the test section roof just over 1m upstream of the exchanger. The rate of introduction had little or no effect on the fouling process apart from duration to saturation. The particles concentration was 0.625 g/m^3, which corresponds to the BS1701 norm. Both particles and exchanger could be sprayed with water. The particles themselves were wood shavings sorted into different size ranges using sieves.

Pressure drop and the proportion and dispersion of particles that contribute to fouling are measured as a function of air speed and particle size mix for iso- and non-isothermal conditions. These are complemented by visualisation. Previous measurements by the authors on mono disperse fouling showed that introduced particles either (i) pass through the exchanger, (ii) become blocked within the inter-fin space, referred to as <u>sub-surface</u> foulant, (iii) are blocked on the <u>outer surface</u> of the exchanger by the air flow but which fall to the floor for zero air velocity or (iv) fall directly onto the floor of the wind tunnel (removed continuously, graded and weighed). The penetration depth of the particles into the exchanger is small, being only about 3 or 4mm. The pressure drop varied linearly with the mass of particles introduced. Both sub-surface and external surface particles contribute to pressure drop but it is the former which presents most problems for any compact heat exchanger.

Results

Pressure drops and particle distribution

The quantities listed above of each component of the binary particle mixture distributed on the exchanger and elsewhere (floor, exit..) for each run were measured. All results were repeatable with a maximum 8% dispersion.

The pressure drop specific to the binary mix of foulant on the exchanger surface was measured continuously and some typical curves are shown on Figure 1. The values represent the contribution to pressure drop by the outer surface and sub-surface foulant only, being the difference between data for a fouled and a clean exchanger in otherwise similar conditions. The pressure drop varies linearly with the mass of particles introduced. Similar curves are found for the mono-disperse case. However, the effects due to a binary mixture can only really be examined via the individual particle distributions. Typical plots of the relative quantities of blocked particles (floor + outer surface + sub-surface (white) and outer surface + sub-surface (grey)) are shown on figure 2a. Figure 2b shows the percentage of sub-surface particles relative to both blocked particles (all) and fouling particles (outer surface and subsurface). Interaction is evident in that the proportion of binary particles blocked by the exchanger is significantly higher than what would be expected by adding the mono-disperse values together Khoshkhoo & McCluskey 2007. This is explained by interaction between particles of different size leading to a greater degree of fouling.

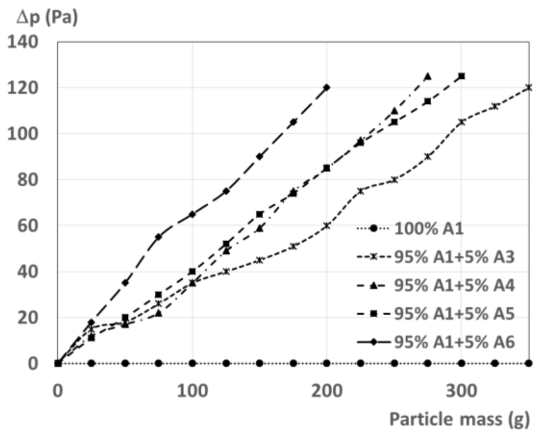

Figure 1: Evolution of pressure drop due to foulant only across a fouled exchanger as a function of the total mass of particles introduced for different size mixtures. Exchanger A; air speed 5 m/s. Dashed lines are included as a visual aid only.

The cumulative nature of the data in Figure 2a hides the influence of the individual particle ranges. The strong influence of the critical size particles (A3) is more evident for sub-surface fouling (Fig 2b) where the blocked proportion is increased by up to 50% more than the cumulated mono-disperse cases. Significantly, the small particles which previously passed through the exchanger unhindered are now increasingly blocked by the presence of the larger particles.

The most dense sub-surface fouling occurs when the critical size particles A3 (size: 0.63 times the maximum IFS) are involved. Any interaction between these and the smaller particles leads to a much greater blocking of the latter. The critical size particles enter into the exchanger and lodge there close to the front. They effectively reduce the spacing for the other particles to pass through causing the smaller particles to be blocked in their vicinity. This is the equivalent of a local reduction of fin spacing thus reducing the effective critical particle size. For fully poly-disperse mixes of particles the consequences will be significant: small particles that otherwise would pass through are now blocked in the sub-surface region and fouling will become very dense.

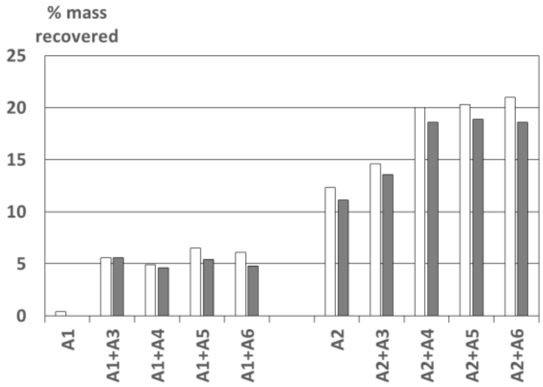

Figure 2a: Ratio of the mass of blocked particles recovered (floor, outer surface and sub-surface) (white) and fouling particles (outer surface and sub-surface) (grey) to the total mass of particles introduced into the air stream for different binary mixtures (exchanger A).

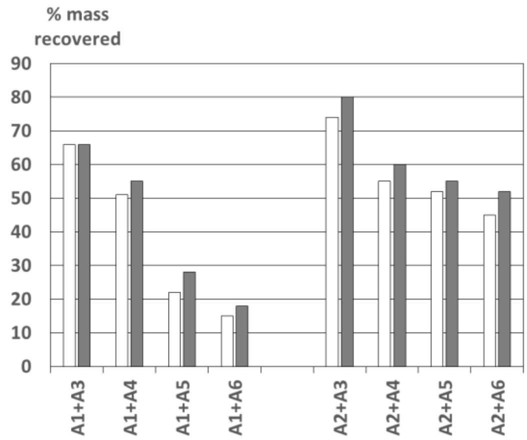

Figure 2b: Ratio of the mass of recovered sub-surface foulant to the mass of blocked (white) and fouling particles (grey) for different binary mixtures (exchanger A).

Observation indicates that the fouling process for a binary mixture has two fairly distinct stages. While small particles initially pass through the exchanger, some of the larger ones get stuck, thus forming what we refer to as fouling nucleation sites. We observed that several of these sites appeared early on in the fouling process. This is the first stage. Once embedded in the inter-fin space, the presence of the large particles reduced the effective passage for the smaller particles and instead of passing through the exchanger; they became blocked around the large particles. Thereafter, the smaller particles are increasingly captured in the sub-surface region in the vicinity of the larger ones and the space fills quickly and densely with small particles. This growth in the capture of small particles is stage 2.

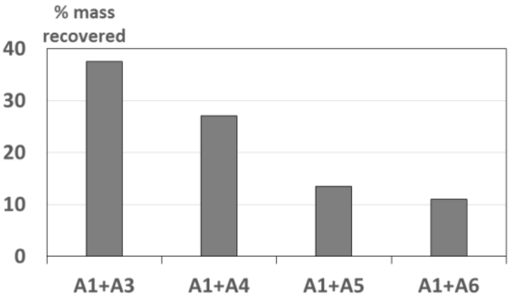

Figure 3: Evolution of the proportion of A1 size particles captured in the sub-surface region as a function of different mixtures.

The interaction between small and large particles is thus a complex and evolving one. From Figure 3 it is evident that the number of smaller particles in the binary mix that are captured in the sub-surface region of the exchanger has a distinct dependence on the size range of the larger particles and that the biggest effect is for the critical size particle.

The pressure drop attributed in part to the smaller particles in a binary mixture is shown on Figure 4. This is calculated by subtracting the pressure drop for a fixed mass of larger mono-disperse particles from that for a binary mixture with the same mass of large particles.

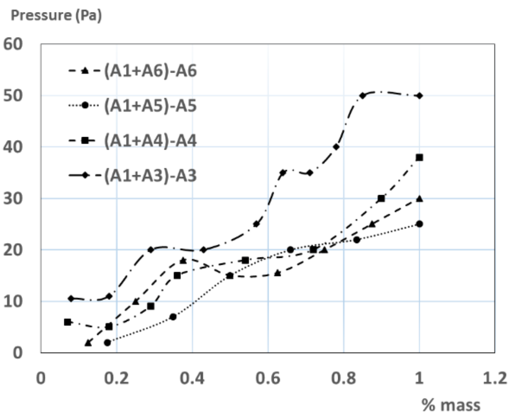

Figure 4: Evolution of the pressure drop across the exchanger due to A1 size particles in different mixtures as a function of increasing mass (divided by the total mass) of particles introduced. Dashed lines are included as a visual aid only.

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This pressure drop is due to A1 size particles being blocked due to the presence of larger particles. There is also evidence that as a result of the small particle fouling, more of the larger particles are now captured than before. This was confirmed via comparison between the percentage mass blocked for the mono-disperse cases and those for the large particles in binary mixtures (Figure 5). The strong increase in the latter shows an unexpectedly significant effect of the small particle fouling on the larger ones.

For all measurements, the influence of the critical particles is evident in that the corresponding curves are systematically the highest for both exchangers and all velocities with or without humidity present.

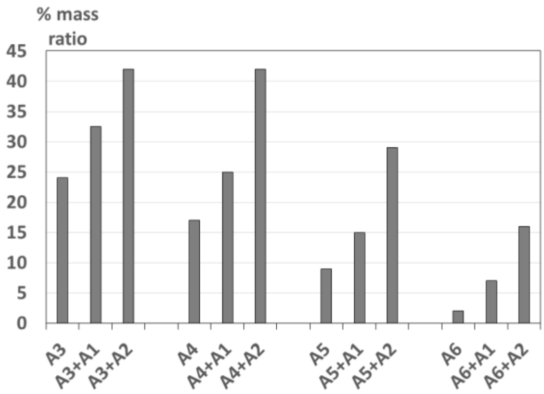

Figure 5: Ratio of the mass of larger particles in the sub-surface region to the total mass of particles introduced for different mixtures. (Exchanger A).

Discussion

Given the complex interaction between the different sized particles it was decided to attempt to define an equivalent critical particle size for a mixture. The reason behind this is to compare binary and mono-disperse results. For binary mixtures, this may well lead to an equivalent size that is not actually present within the mixture itself. Rather than simplistically taking a weighted geometric average of two particle diameters, the chosen method of definition involves making a direct correlation between the percentages of mixed particles blocked on the exchanger surface (e.g. Figures 2a & b) and the curves taken for the mono-disperse case (Figure 6) Haghigi-Khoshkhoo & McCluskey 2007. This last is a monotonically increasing function with particle size until the fouling reaches saturation. The values of the percentage blocked in the binary case will therefore correspond to a single value for particle size on this monotonic curve. This will be defined as the equivalent size for the mixture. Defining the equivalent size in this way represents an attempt to account for the unexpectedly strong particle interaction beyond simple geometric considerations. The result of this comparison is shown in Table 3. As expected, these equivalent (or averaged) values are not in either of the size ranges present within the binary mixture. Care must be taken nevertheless to avoid assuming that particles of a given equivalent size have the same dynamic behaviour as mono disperse particles of that size.

The usefulness of defining the equivalent size becomes clear with the definition and discussion of the fouling factor F. This is defined by Cowell 1990:

$$F = (\Delta p_{total} - \Delta p_{exchanger})^{1/2} / \rho v^2 \qquad (1)$$

and corresponds to the non-dimensional pressure drop due solely to the foulant. F has been calculated for both mono-disperse and binary mixtures of particles.

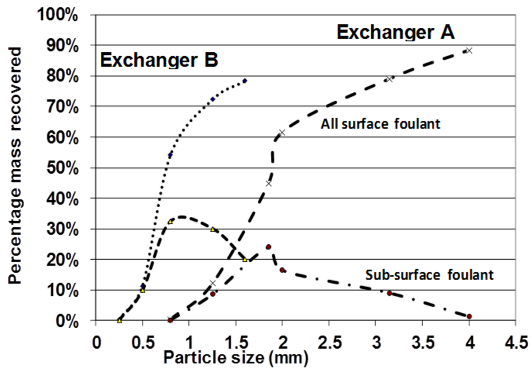

Figure 6: Evolution of the mass of foulant recovered on the exchanger surface as a function of particle size for discrete size ranges. Taken from Haghighi-Khoshkhoo & McCluskey 2007 with kind permission.

In both cases, F is constant with air velocity, indicating that the foulant plays the role of an extra filter in front of the exchanger. It is usual to plot F as a function of particle size. Non-dimensionalising the particle size in present case is done with the diameter D_m, defined at the diameter of the largest sphere that can be inscribed in the inter-fin spacing. This value is easily quantified for any exchanger. This will effectively remove any dependence on the specific dimensions of an individual exchanger. The curves for binary mixtures can also be plotted as a function of the non-dimensional equivalent particle size.

During experiments we noted that due to gravitational effects on the particles, the upper zones of the exchangers were not reached by the foulant. The extent of this clear zone varied with

applied wind speed. Thus for each experiment, the clear zones were blocked off with board.
Furthermore, it required different amounts of foulant to bring about the same pressure drops across the exchanger depending on fin spacing. It was therefore considered more logical to plot F per unit mass of particles injected and per unit fouled surface area of the exchanger. When plotted against the non-dimensional (equivalent) particle size (Figure 7), the results show a tendency to collapse onto a single curve, indicating a common behaviour for different exchangers and for any mixture of particles. There is some dispersion of results, but this is far less than could have been expected, given the nature of this type of experiment. Very similar results are found for a wetted exchanger.

The variation of F/kg.m^2 appears exponential. However, it is not wise to attach physical meaning to this. The domain of values is small, reaching to the equivalent of the critical particle size. This is because the mixture has only 5% by mass of larger particles and the averaged size for the mixtures will be relatively small. For higher equivalent sizes (*i.e.* increasing large particle size or the percentage of larger particles) there will no doubt be a levelling off of the curves, although such a situation would only be of academic interest at best.

Table 3: Equivalent particle sizes for different binary mixtures of particles. LHS Exchanger A, RHS Exchanger B. In parenthesis is the equivalent range.

Composition	Equivalent size	Composition	Equivalent size
100% A1	0.80 (A1)	100% B1	0.25 (B1)
95% A1 + 5% A3	1.00 (A2)	95% B1 + 5% B3	0.38 (B2)
95% A1 + 5% A4	1.03 (A2)	95% B1 + 5% B4	0.40 (B2)
95% A1 + 5% A5	1.04 (A2)	95% B1 + 5% B5	0.40 (B2)
95% A1 + 5% A6	1.05 (A2)		
100% A2	1.26 (A2)	100% B2	0.50 (B2)
95% A2 + 5% A3	1.32 (A3)	95% B2 + 5% B3	0.54 (B3)
95% A2 + 5% A4	1.41 (A3)	95% B2 + 5% B4	0.55 (B3)
95% A2 + 5% A5	1.44 (A3)	95% B2 + 5% B5	0.53 (B3)
95% A2 + 5% A6	1.47 (A3)		

However, the fouling factor only translates the quantity of foulant on the exchanger surface. It does not indicate the type of fouling involved, i.e. sub-surface or otherwise.

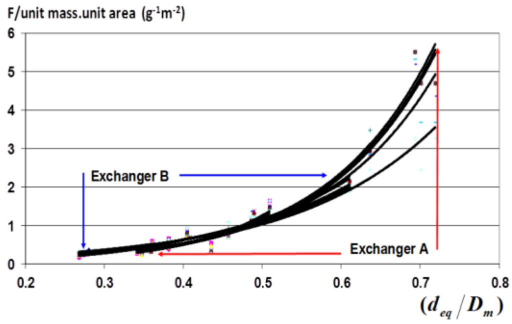

Figure 7: Variation of the fouling factor per unit mass and unit exchanger surface area as a function of non-dimensional equivalent particle size for all binary mixtures of particles examined in both exchangers. (Air speed is 5m/s).

Heat Transfer

Non isothermal results taken for the binary mixtures will show no change compared to the mono-disperse results as regards pressure drop and fouling rates. However, previous results indicated that wind tunnel tests showed no effect on heat transfer due to fouling. This is an unexpected result. Several series of wind tunnel tests were carried out to quantify the effects of fouling on heat transfer across the exchanger. Exchanger A with an input temperature of 60°C was continuously fouled with particles of critical size. For all air speeds, the temperature drop did not change with increasing fouling (13°C at 1 m/s to 25°C at 5 m/s), although the air side pressure drop across the exchanger did show a strong increase. These results were confirmed on exchanger B. Heat removal from the exchanger is directly proportional to air flow over it. In a closed test section wind tunnel the direction of the air flow will be altered due to partial blocking but unless there is strong blockage, the overall mass flow rate of the air through the exchanger does not change. The airflow will be forced through the exchanger and will thus maintain the heat removal with little alteration. This corresponds with previous observations as well as our own.

In more realistic situations, as the exchanger is fouled, the airflow through it will be seriously altered. If this is diminished, then so will the temperature removal from the exchanger. A further set of experiments were carried out but this time a slot was opened in the wind tunnel test section just in front of the exchanger. For the clean exchanger the same results were found as for the closed test section. Once the fouling began and blockage increased, the airflow diminished through

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the exchanger, the rest escaping out through the slot, and Figure 8 shows the results on the temperature difference for exchanger B. It can be reduced by up to 50% in the present experiments obviously leading to over-heating.

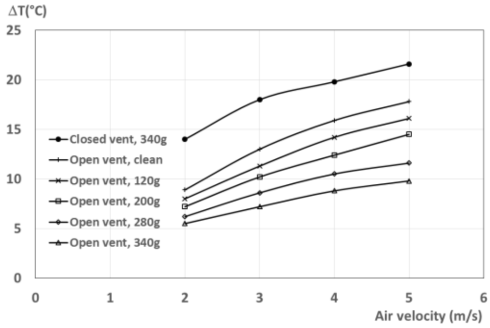

Figure 8: Temperature drop across increasingly fouled exchanger in an open vent wind tunnel as a function of mean air flow velocity.

One must conclude that attempting to take non-isothermal measurements in a closed test section wind tunnel will not give any useful information on real performance. It is possible to design the vehicle front to force the airflow through the exchanger and not around it when fouled, but this would more likely increase compaction of the foulant rendering cleaning very difficult.

Conclusion

Measurements show that fouling of a compact heat exchanger by a binary mix of small (95% by mass) and large (5%) particles is not simply an additive effect. There is an interaction between both size ranges of particle causing increased fouling. When the critical size particles are involved the extent of sub-surface fouling is significantly augmented. The presence of large particles blocked at the front of the exchanger locally reduces the effective open area through which the smaller particles pass causing them to be deposited in the vicinity. This is true for even the smallest particles which otherwise pass through the exchanger unhindered. The serious consequence is that eventually all smaller particles will correspond to a critical fouling size as the fouling evolves and block the exchanger in a compact deposit. However, the increased quantity of large scale particles that are blocked due the presence of smaller ones is not yet explained and requires further investigation.

Finally, questions arise as to the validity of thermal performance results on fouled exchangers when experiments are carried out in closed test section wind tunnels.

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